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Configuring Your Data Acquisition or Test and Measurement System for Maximum Noise Immunity

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One of the most common plagues faced by test measurement systems is noise, defined as any unwanted signal imposed on a desired signal. Noise can degrade a measurement to the point of making it meaningless. However, the first consideration in reducing or minimizing noise is to make sure that you are using the correct type of instrumentation and system architecture to make your measurements.

Signal Level and Sensitivity is the Starting Point

Knowing the level of the signal or sensor's output and the level of sensitivity required for the measurement is the starting point. For instance, signals from Josephson junction standards requiring nanovolt sensitivity can only be measured by precision benchtop instruments, while thermocouples that output millivolts can use PC-based test instrumentation. The required accuracy, resolution, and speed of the measurement are also important determinants an engineer must consider when deciding how to collect and measure data. This means that applications requiring streaming data-to-disk and real-time graphical displays require a PC-based solution.

Environment is a critical factor in selecting a measurement system. Are the measurements to be made in a plant environment with electrically noisy machinery or in an electrically quiet laboratory setting?

Test Instrumentation Architecture

In today's test environment you have a broad selection of test equipment architectures. There are three major types of instrumentation composing these architectures.

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Benchtop Instruments. The most accurate and sensitive instruments are benchtop instruments. These are conventional instruments, enhanced with many new and improved features, such as graphical displays, push button and menu programming. The instruments can also be controlled from a PC using the Standard Commands for Programmable Instruments (SCPI), an extension of the IEEE-488.2 protocol.

Distributed Instruments. Distributed instruments have recently been introduced into the marketplace by several manufacturers. This type of instrumentation equipment provides a new architecture that consists of miniaturized instruments located close to the test signal and then networked back to a PC. Induced cable noise is minimized because of the short distance between the signal and the instrument.

PC-based Test Instrumentation. PC-based test's primary compelling attributes are measurement speed and the ability to capture large amounts of data. There are two basic configurations in use today. The most common configuration finds the analog test signal connected to a PC plug-in board, which is located either in a computer slot or in the PC's parallel ports. The other configuration consists of chassis-mounted boards where the chassis can be rack mounted and located a significant distance from the PC. The chassis contains measurement, multiplexing, analog-to-digital conversion, and signal conditioning boards for networking fully processed digital signals to the PC. The chassis system effectively expands the size of the measurement system to a larger number of channels than is available with the number of board slots inside a PC.

Other Parameters to Consider. While the instrumentation's sensitivity is the starting point, important parameters determining its sensitivity is the instrument's resolution and speed. For a specific measurement range, the greater the resolution, the greater the sensitivity. High speeds normally result in lower sensitivity and vice versa. Accuracy, the measure of the closeness of agreement between a measured value and that of a primary standard, is also important. Accuracy is stated as a percentage, in ppm or in bits, depending on the particular instrument. The highest accuracy, sensitivity, and resolution is provided by benchtop instruments.

The parameters discussed above are presented in Table 1 for each of the three types of instrumentation. However, you must be aware that these figures reflect the highest or best value for each parameter that can normally be attained for that type of instrumentation and that all of these values cannot be attained simultaneously.

Table 1. Typical attributes of instrumentation architectures.

Measurement Parameter	Benchtop Instrument	Distributed Instrument	PC-Based Test Instrument
Sensitivity	1 nanovolt	100 nanovolts	5 microvolts
Resolution	20- to 28-bits	16- to 20-bits	12- to 16-bits
Sample Rate	2 kS/s	30 kS/s	330 kS/s

Of course, the decision on what kind of hardware to use involves tradeoffs to get the combination of sensitivity, accuracy, resolution, and speed that is required to make the measurement.

Noise Immunity

Certain types of measurement instrumentation have noise immunity built in. This includes both benchtop and distributed instruments. These instruments use internal techniques—such as filtering and integration—to reduce noise. However, there is no built-in noise immunity in PC-based plug-in boards and PC-based external chassis systems. Instead, PC-based test systems use software that provides averaging techniques to reduce the noise from the measurement and/or signal conditioning add-ons, such as filters. One of the inherent disadvantages of the PC is its noisy bus. This limits the PC plug-in boards from making sensitive measurements.

Minimizing Noise

A myriad of conditions may cause noise in low-level instrument-based systems and PC-based test systems. Many of the conditions causing noise in low-level instrument-based measurement systems do not apply to the PC-based test systems because of the much higher level of the signals being measured by the latter. The noise conditions are shown in Table 2 by the level of the signal to be measured.

Table 2. Noise conditions affecting instrument-based and PC-based test systems.

Low-Level Signal Instrument-Based	Higher-Level Signal PC-Based
External 60 Hz line noise	External 60 Hz line noise
Normal mode voltage (NMV)	Normal mode voltage (NMV)
Common mode voltage (CMV)	Common mode voltage (CMV)
EMI and RFI	EMI and RFI
Magnetic fields	Magnetic fields
Ground loops	Ground loops
Johnson noise	Noisy PC bus
Noise currents	
Thermoelectric EMF	
Electrostatic coupling	
Piezoelectric effect	
Triboelectric effect	

Many of the noise conditions listed in Table 2 are a direct function of the design of the test system. Table 3 lists some of the major design factors that are instrumental in determining the noise level of each type of test system.

Table 3. Design factors for consideration in instrument-based and PC-based test systems.

Low-Level Signal Instrument-Based	Higher-Level Signal PC-Based
Cable type—shielded, twisted, low noise	Cable type—shielded, twisted, low noise
Cabled distance between signal and instrument	Cabled distance between signal and PC
Connection design	Distributed instrument networked to PC or chassis-mounted board outside PC
Signal conditioning—built-in	Signal conditioning—add-on

We will discuss each of the noise conditions listed in Table 2 and provide information on how to eliminate or at best reduce the noise condition to levels that won't interfere with making accurate measurements.

Magnetic Coupling as A Source of Noise

A magnetic field passing through a loop in a test circuit will generate a magnetic EMF (voltage) that is proportional to the strength of the field, the loop area, and the rate at which these factors are changing. Even the earth's relatively weak magnetic field can generate nanovolts in dangling test leads, so leads must be short and immobile when making low-level measurements. Magnetic field effects can be minimized by following these guidelines:

- Locate the test circuit as far away as possible from such magnetic field sources as motors, transformers, and magnets.
- Avoid moving any part of the test circuit within the magnetic field.
- Minimize the loop area by keeping leads as short as possible and twisting them together.

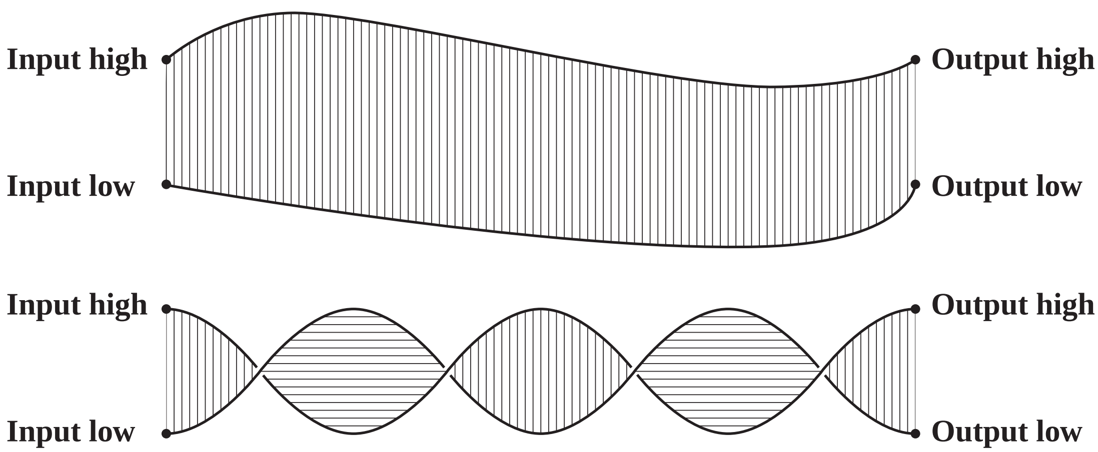


Figure 1. Magnetically induced noise voltages are proportional to the area of the current loop formed by the signal leads (top). Twisting the leads can virtually eliminate those voltages. Noise contributions from the horizontally shaded loop areas cancel contributions from those with vertical shading.

When you are unable to avoid the effects of magnetic fields, shielding is helpful. The extent of shielding depends on the environment, signal levels measured, and the equipment configuration. There are three levels of shielding; each level is described by the extent of the circuit and instrumentation enclosed.

1. Only the test circuit is enclosed, with shielded leads running to the test instrument. These are in the form of shielded twisted pair and triaxial cables. Triaxial cable has three conductors: one conductor surrounded by an inner shield and an isolated

outer shield. Generally, the inner shield is connected to signal low and the outer shield is connected to power-line ground. If guarding is used, the inner shield is connected to guard potential and the outer shield to signal low or ground.

2. Both the test circuit and the instrument are covered by a shield, such as a mu-metal box.
3. The test circuit, instrument, and person doing the test are shielded, such as in a screen room. This level of shielding would be used for measuring extremely low signal levels.

One way that you can verify pickup from AC fields is to monitor the analog output of the instrument with an oscilloscope. You should be able to see the induced noise riding on the test signal and, based on its amplitude and pattern, apply the appropriate level of shielding.

Many specific types of noise caused by magnetic coupling are identified according to the source or where they appear in the test circuitry. These include 60Hz line noise, normal mode voltage, and common mode voltage.

External 60Hz Line Noise Voltage Pick-up. This is undoubtedly the most common form of external noise pick-up caused by magnetic coupling. The 60Hz line noise is a common occurrence, especially near fluorescent lights. The signal components that it superimposes on the DC signal being measured may result in highly inaccurate and fluctuating measurements. To reduce this noise, use shielded, twisted-pair input leads. Keep circuits away from external sources.

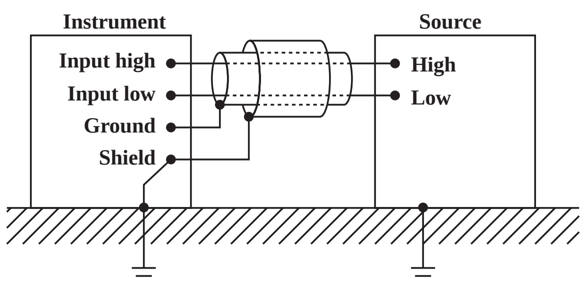
Normal Mode and Common Mode Voltages. Normal mode is a noise voltage input between the high and low input terminals of an instrument or PC-based test board. Common mode voltage is a noise voltage input between input low and chassis ground of an instrument or between a PC-based test board's terminals and ground. Common mode noise is usually less severe than normal mode noise. The most common source of normal mode and common mode voltages is 60Hz line noise, but it can be induced by any magnetic field operating in the area. Use shielded, twisted pair cable to reduce this noise. Also, to minimize common mode noise, connect shields to a single point in the test system. Normal mode rejection ratio and common mode rejection ratio define in decibels how well test instrumentation rejects or attenuates this type of noise.

Other Sources of Noise

In addition to the major or predominant sources of noise discussed above, there are other noise sources that affect measurements. However, with the exception of radio frequency interference (RFI) and electromagnetic interference (EMI) and ground loops, most of these sources are only considerations when making low-level or sensitive measurements.

RFI and EMI. RFI (>105Hz) and EMI (<105Hz) are general terms used to describe electromagnetic interference over a broad range of frequencies across the spectrum. RFI or EMI is radiated and can be caused by steady-state sources, such as TV or radio, or it can be caused by impulse sources, as in the case of high-voltage arcing. This type of interference may show as a steady-state offset or it may result in noisy or erratic readings. The cause of a constant reading offset may be input amplifier overload or DC rectification at the instrument's input. Almost any metal-to-metal joint can form a junction diode and when RF is induced across the junction, rectification and strong harmonics may result.

Figure 2. The maximum EMI protection for differential-measurement signal leads comes

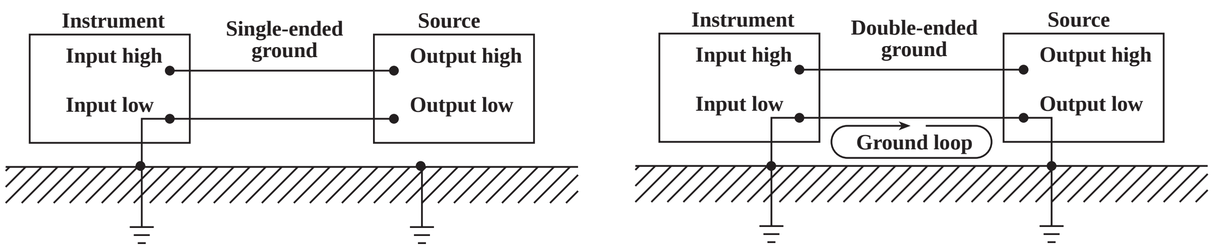


from surrounding the actual signal lines with a guard electrode tied to signal low, and surrounding that with a shield tied to ground.

You should not attempt to make low-level measurements near powerful TV or radio transmitters or any interference sources. Shielding the test leads and device under test may be sufficient. However, it may be necessary to construct a screen room to sufficiently attenuate the troublesome signal. If this fails, then filtering is the remaining solution.

Ground Loops. Noise and error voltages can result from ground loops. When the source and measuring instruments are both connected to a common ground bus, a loop is formed. The voltage difference between the signal source and instrument grounds will cause current to flow around the loop, creating a noise voltage in series with the source voltage. The cure for ground loops is to ground all equipment at one point. This is easily accomplished by using isolated power supplies and isolated instruments. Then, all system grounds should be connected together in a single, good earth-ground point.

Figure 3. Signal-low lines should be tied to ground at only one point (left). Tying at a



second point creates a ground loop that soaks up any available AC magnetic field energy and applies it directly to the measurement input.

Johnson Noise. Johnson or thermal noise is the noise in a resistor caused by the thermal motion of charge carriers. It has a white noise spectrum and is determined by the temperature, bandwidth, and resistance value. Since all real voltage and current sources contain an internal resistance, they exhibit Johnson noise. The only way to control Johnson noise is to vary the bandwidth and temperature. As the bandwidth and temperature decrease, the Johnson noise decreases. Current noise decreases with increasing resistance, while voltage noise increases.

Noise Currents. These are currents induced by electrostatic coupling or vibration of the test equipment. The solution is to avoid any high voltage nearby and/or movement. To eliminate noise currents, use shielding and low-noise cable. Isolate the instrumentation and all circuitry from vibration.

Thermoelectric EMFs. Thermoelectric EMFs are small voltages developed at the junctions of dissimilar metals. The magnitude of the voltage depends both on the type of metals used as well as the temperature differences between junctions. This noise will add to the desired signal, producing an error in measurement. Thermoelectric EMFs can be minimized by using only clean, crimped-on copper-to-copper connections and by keeping all junctions at the same temperature.

Electrostatic Coupling. Electrostatic coupling can occur when a wire with an applied voltage (usually a high voltage) or a charged object is brought close to the test circuit. A stray current can be induced into the circuit by varying the voltage or by moving or vibrating the wire or charged object. Error currents from electrostatic coupling can be avoided by keeping all charged objects, including people, and conductors away from sensitive areas of the test circuit.

Avoid movement and vibration in the vicinity of the test area. For low-level current measurements, a metal enclosure should be placed around the device under test with the enclosure connected to the test circuit common ground. Capacitive coupling between an electrostatic source and signal conductors can be reduced by shielding those conductors with a grounded metal shield. However, this may not be adequate for low-level measurements and guarding may be required to minimize the effects of both noise coupling and leakage currents.

Piezoelectric Effects. Piezoelectric effects are generated when mechanical stress is applied to certain insulating materials, such as crystalline materials used for insulated terminals and interconnecting hardware. To minimize this effect, it is important to choose good insulating materials and to make connecting structures as rigid as possible.

Triboelectric Effects. Triboelectric currents are generated by charges created between a conductor and an insulator as a result of friction. A typical example would be electrical currents generated by insulators and conductors rubbing together in a coaxial cable. “Low-noise” cable greatly reduces this effect. Triboelectric effects can be minimized by avoiding cable vibration, expansion, and contraction. This can be accomplished by keeping all cable connections short, away from temperature changes, and fastened to a non-vibrating surface.

Measurement System Design Factors

Some of the measurement system design factors that you can use to minimize noise signals are:

- Minimize the cabling distance between the signal source and measuring device. In the case of PC-based test, use a distributed instrument located as close to the source as possible and networked back to the PC.
- Use low-noise shielded cable for all cable runs.
- Use signal conditioning to amplify the level of low-level signals above that of interfering noise.
- Use single-point grounding to eliminate ground current loops.
- For PC-based test, use a high impedance feedback path to provide a current drain path, thereby avoiding ground loops.
- Isolate the signal source and measurement hardware to prevent ground loops.

Isolation of a high voltage input or an input operating in the vicinity of a high voltage source also protects the test equipment as well as test system users.

- Use single-ended inputs to eliminate CMV and to make sensitive measurements.
- Use differential inputs for better noise immunity when NMV is present and signal levels are low.
- Stabilize the ambient conditions when making low-level measurements.
- Secure all leads, especially when making low-level measurements.
- Use guarding to make critical high-impedance voltage measurements, current measurements, and resistance measurements.

Summary

To make accurate low-noise measurements, you must choose the proper type of test equipment. In most cases, the signal level and the level of sensitivity required for the measurement are the starting point for determining the test equipment architecture required. Benchtop instruments are used to make low-level measurements, requiring high levels of sensitivity, while PC-based test can be used for higher level signals requiring lower sensitivity. However, the accuracy, resolution, and sampling speed required are also considerations. Next item is managing external factors with good system design, which may be even more important. These factors are normally controlled by using test configurations, connections, and techniques that avoid or minimize the sources of error. Using hardware, fixtures, cables, other accessories, and good practices compatible with the test instrumentation will help assure the successful application of these techniques. A test instrumentation supplier that offers a wide range of test hardware and detailed application assistance can help you to make your low noise test measurements more efficiently.

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